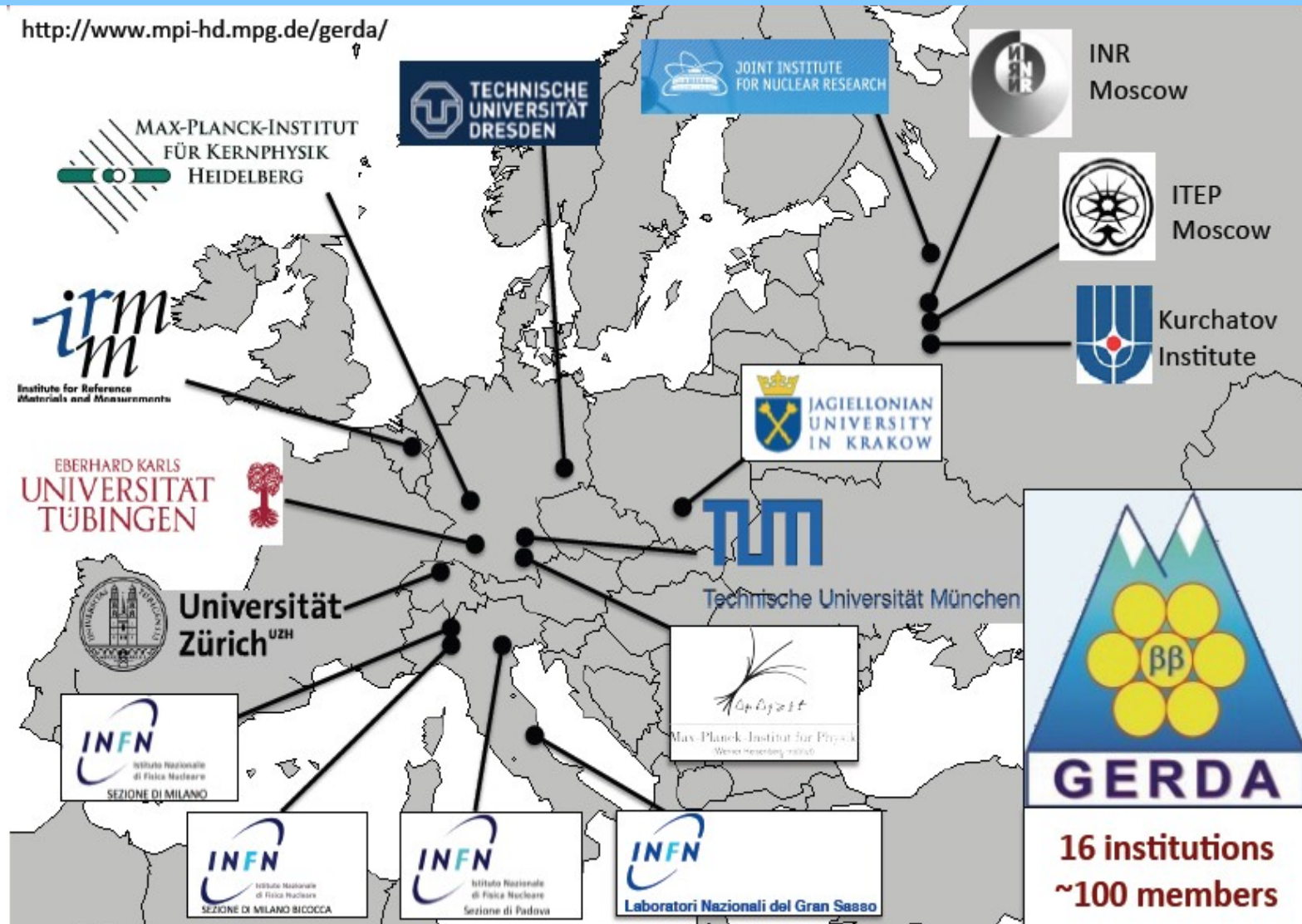# Limit on neutrinoless double beta decay of ^{76}Ge by the GERDA experiment

Bernhard Schwingenheuer (Max-Planck-Institut Kernphysik, Heidelberg)
for the collaboration
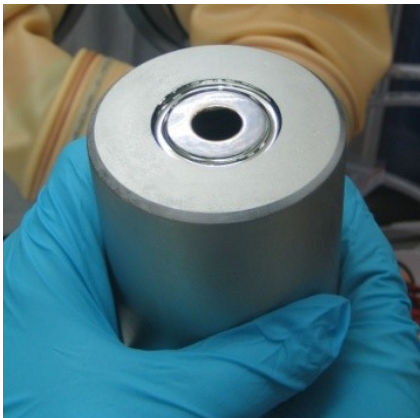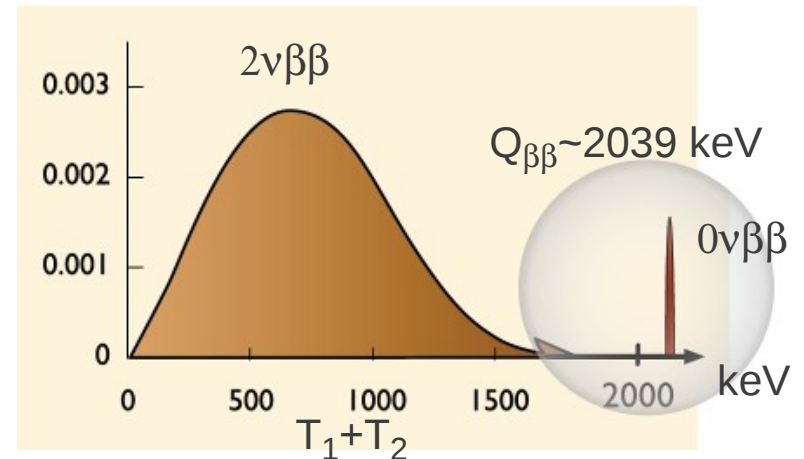TAUP 2013, Asilomar (CA, USA)

The collaboration

Introduction

GERDA searches for $0\nu\beta\beta$ decay $^{76}Ge \rightarrow\ ^{76}Se + 2\ e^-$

detector = Ge diode = source

^{76}Ge enriched to ~86%

Energy resolution
FWHM~0.2% @ $Q_{\beta\beta}$

9 semi-coaxial detectors:
ANG1-5   Heidelberg-Moscow
RG1-3   IGEX experiment
GTF112   natural Ge
(all reprocessed at Canberra)

5 BEGe detectors:
GD32B-35C new, inserted later

ANG1, RG3, GD35C not used
in analysis,
remaining = 17.6 kg enriched det.

lock & glove box
for string insertion

charge sens amp.
low radioactivity

string with 3 detectors
low mass support

$64\ m^3$ LAr

inside water tank

590 m^3 pure water / Cherenkov veto

- idea Gerd Heusser 1995
- GERDA proposal 2004
- construction 2006-2010
- commissioning 2010-11
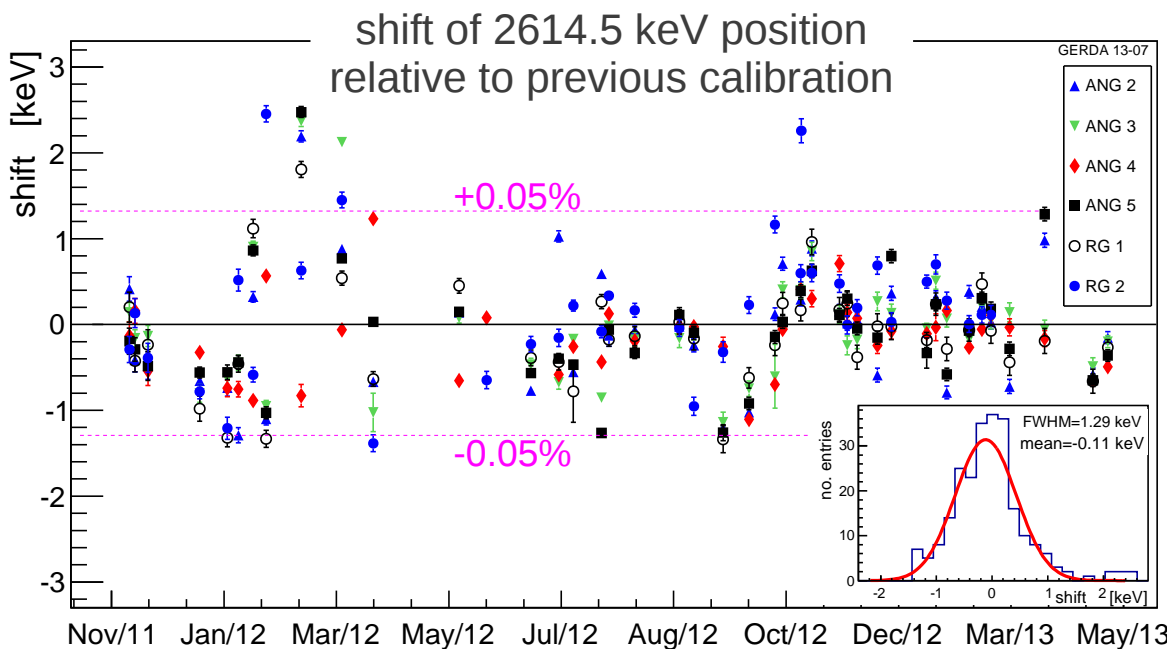- physics data Phase I 2011-13
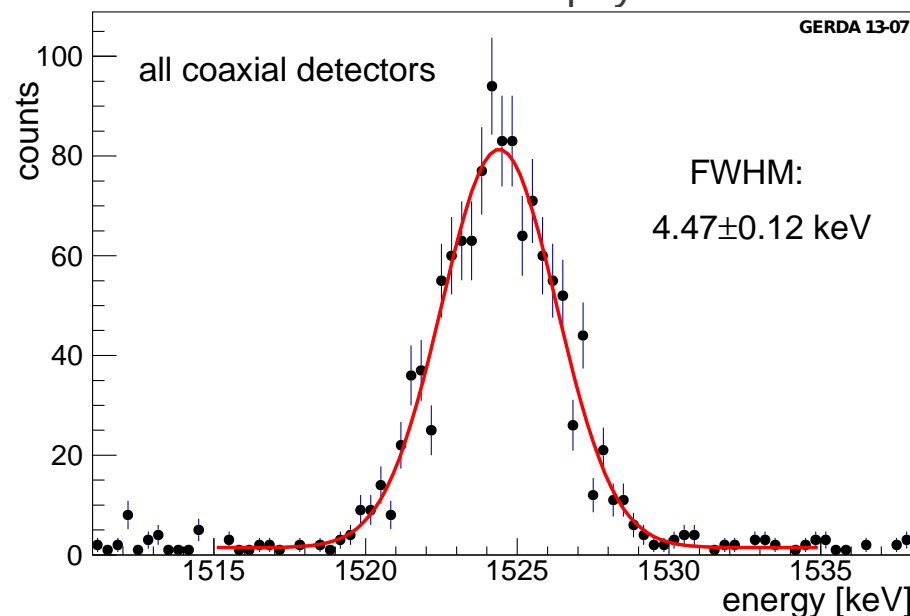
Calibration & data processing

Processing: diode → amplifier → FADC → digital filter → energy, rise time, pulse shape, ...

Selection: anti-coincidence muon / 2nd Ge (~20% rejected @ $Q_{\beta\beta}$),
        quality cuts (~9% rej.), pulse shape discrimination (~50% rej.)

Calibration: ^{228}Th (bi)weekly & pulser every 20 seconds for short term drifts
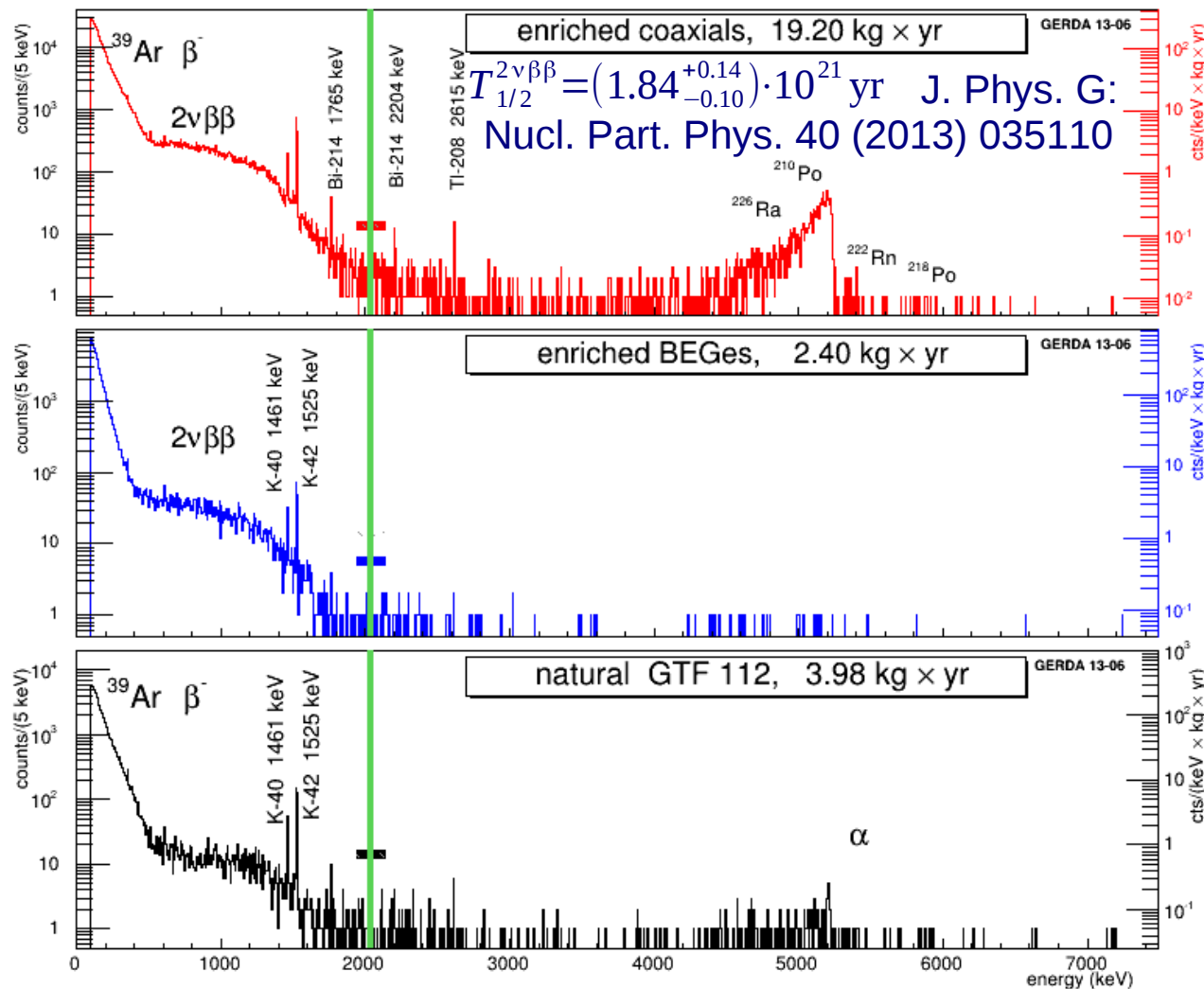

shift of 2614.5 keV position relative to previous calibration

+0.05%

-0.05%

FWHM=1.29 keV
mean=-0.11 keV

GERDA 13-07
△ ANG 2
▽ ANG 3
◆ ANG 4
■ ANG 5
○ RG 1
● RG 2

shifts are small compared to FWHM ~ 0.2% $Q_{\beta\beta}$

1524.6 keV ^{42}K line in physics data

all coaxial detectors

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FWHM:
4.47±0.12 keV

**peak pos. within 0.3 keV at correct position
FWHM ~ 4% larger than expected
from calibration data**

The figure shows three physics spectra:
- enriched coaxials, 19.20 kg × yr, GERDA 13-06
- enriched BEGes, 2.40 kg × yr, GERDA 13-06
- natural GTF 112, 3.98 kg × yr, GERDA 13-06

$$T_{1/2}^{2\nu\beta\beta} = \left(1.84^{+0.14}_{-0.10}\right) \cdot 10^{21} \text{ yr}$$

J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

blind analysis:
evt in $Q_{\beta\beta}$ ± 20 keV not reconst.
until calibr. + cuts fixed

Phase I data split into 3 sets
  - "golden coax" = 17.9 kg yr
    all semi-coax data but 4 weeks
  - "silver coax" = 1.3 kg yr
    4 weeks when BEGe inserted
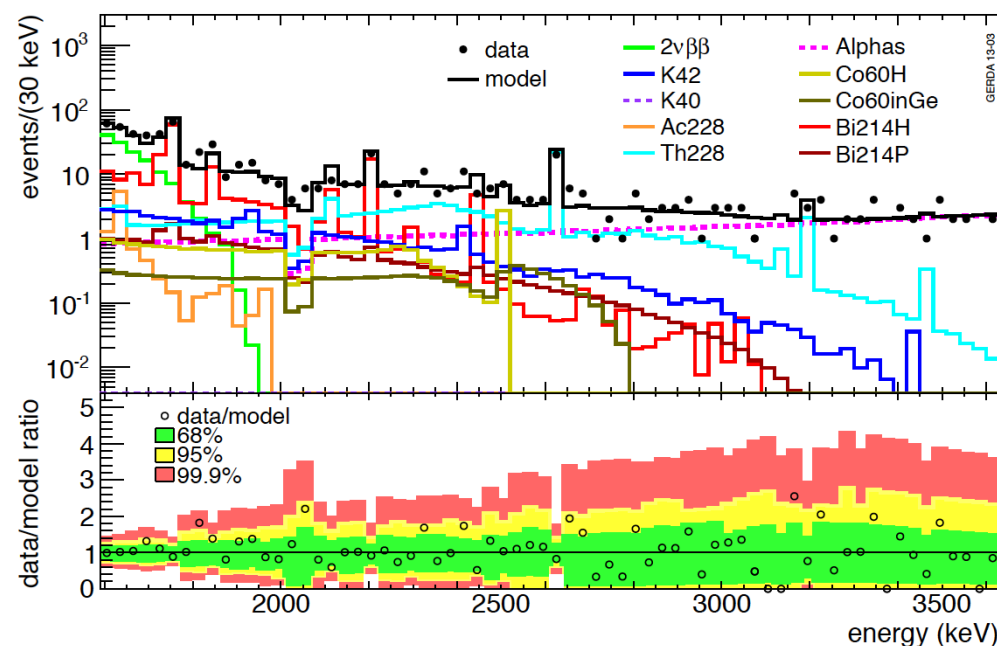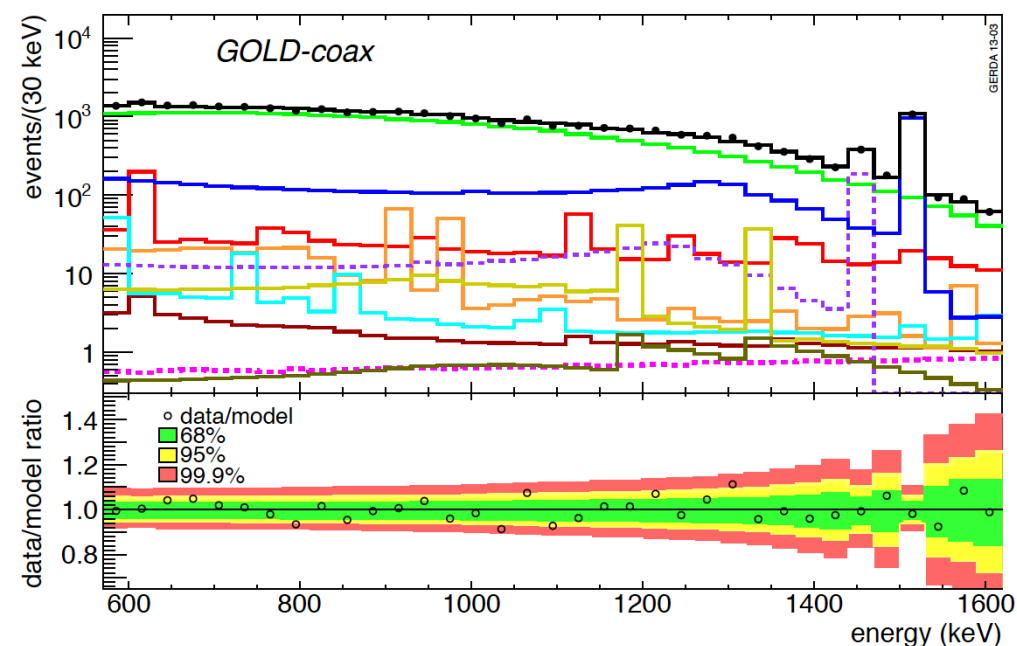 - "BEGe" = 2.4 kg yr

background level:

	GERDA	HdM[1]
2615 keV [cts/(kg yr)]	1.1±0.3	16.5±0.5
1764 keV [cts/(kg yr)]	3.3±0.5	30.7±0.7
avg @ $Q_{\beta\beta}$ [cts/(kev kg yr)]	0.018± 0.002[1]	0.16± 0.005[2]

[1] "golden coax", 1930-2190 keV, no PSD
[2] Heidelberg-Moscow 1995-2003 data, 2-2.1 MeV, no PSD
[1] Oleg Chkvorets, PhD thesis, NIM A522 (2004) 371.

- simulate known & observed backgrounds
- fit combination of MC spectra to data
  in interval 570 keV – 7500 keV
  → relative contribution of backgrounds
- tested several comb. of position & contrib.
  → no unique determination

close background sources dominate:
^{42}Ar, ^{228}Th & ^{226}Ra in holder,
α on detector surface,
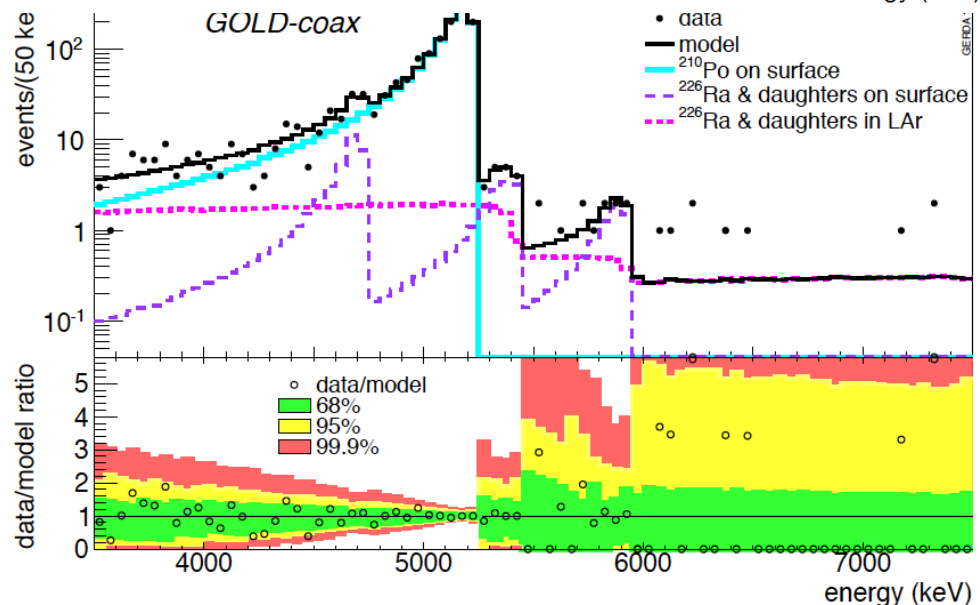
background model @ $Q_{\beta\beta}$

"minimal fit" (all known contributions)
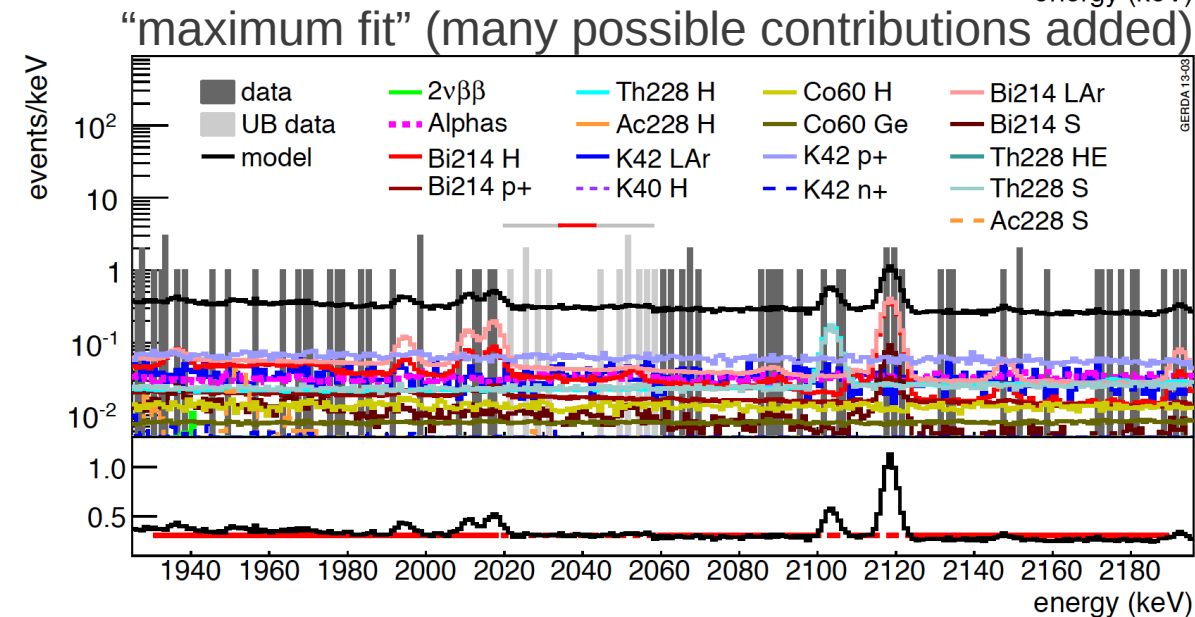
"maximum fit" (many possible contributions added)
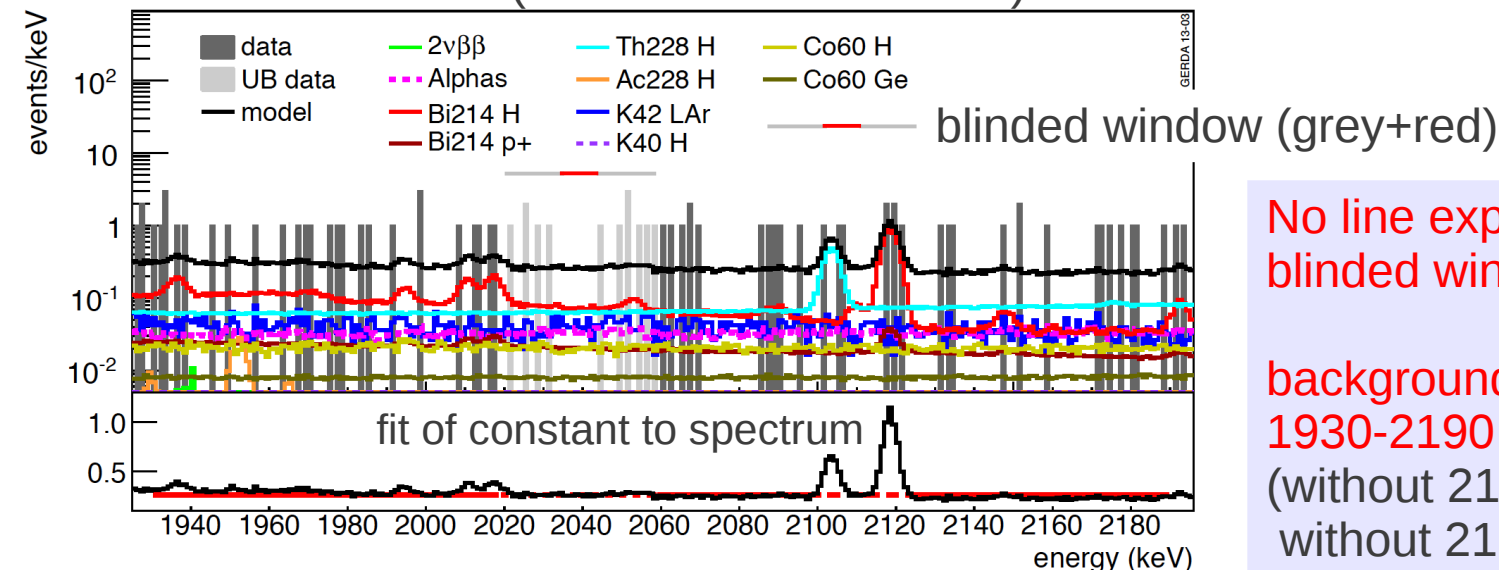
No line expected in the blinded window

background flat between 1930-2190 keV
(without 2104±5 keV,
 without 2119±5 keV),

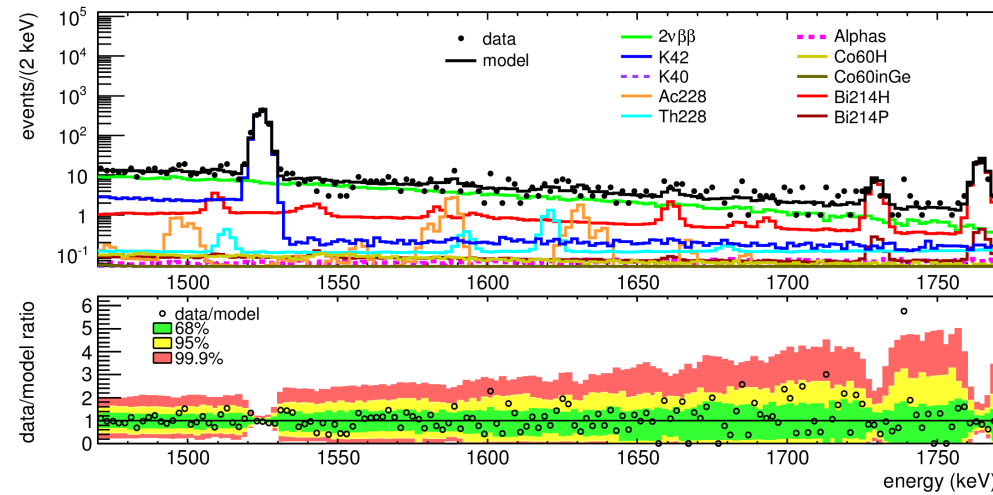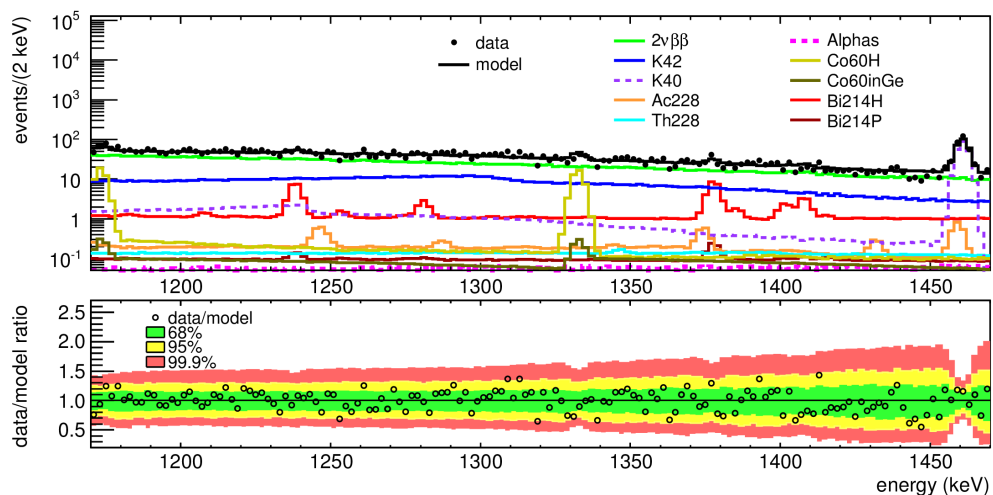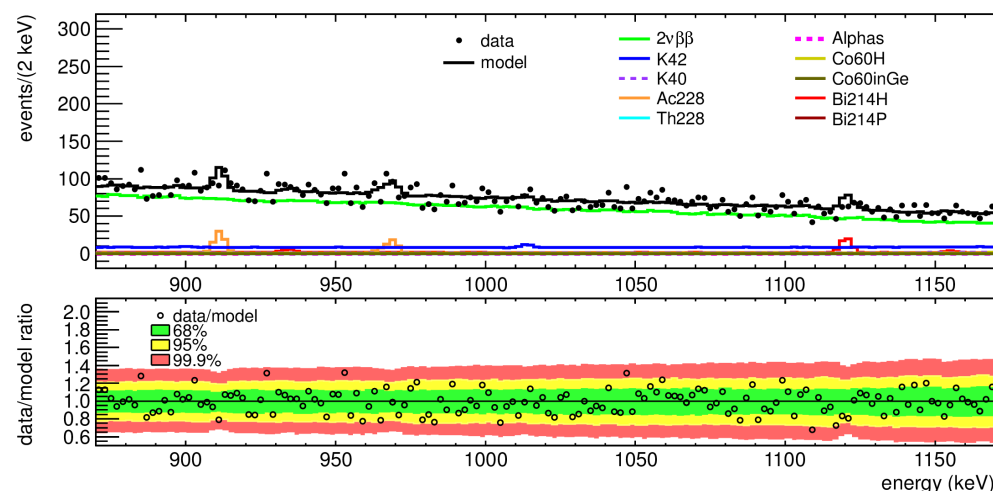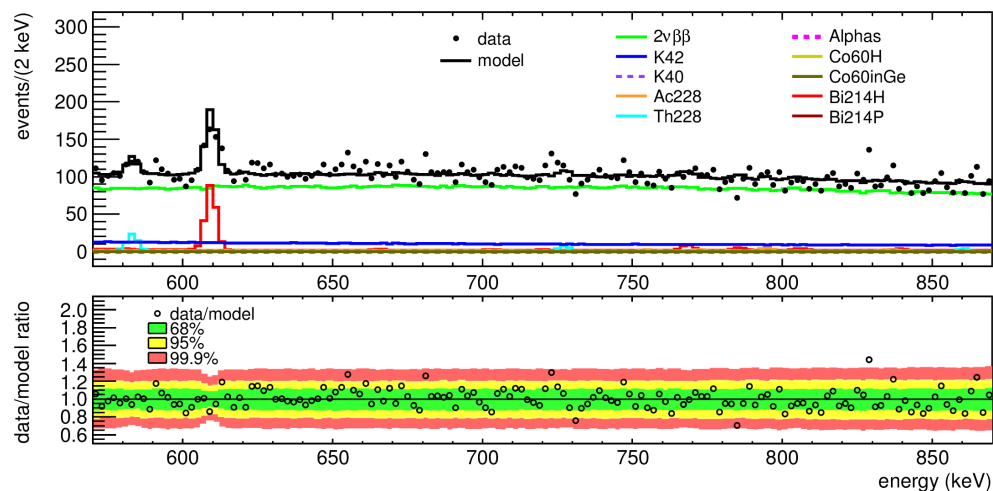expect << 1 event in other weak ^{214}Bi lines (e.g. 2017, 2053 keV)

partial unblinding (grey window) after fixing of calibration & bkg model, no line in grey interval, expected 8.6-10.3 evts in grey part & see 13 events
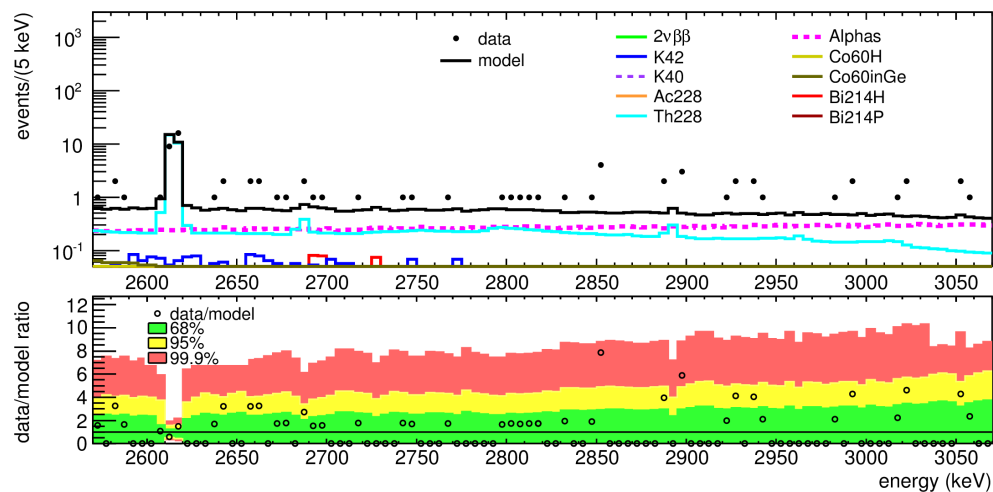
background model in small binning

"minimal model": fit to "golden coax" data Nov 2011 – March 2013 (= 15.4 kg yr) with 30 keV bins
here: scale the fit to total "golden coax" exposure of 17.9 kg yr and compare to physics data of entire period
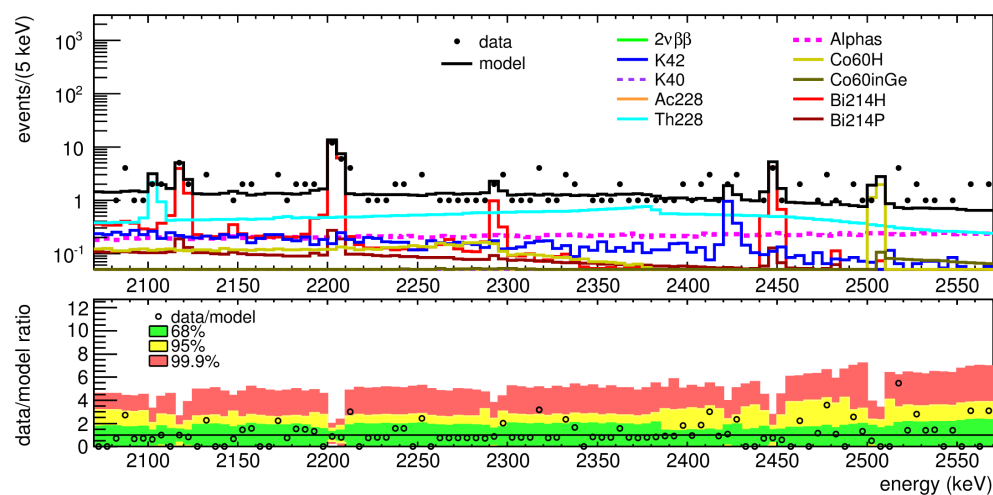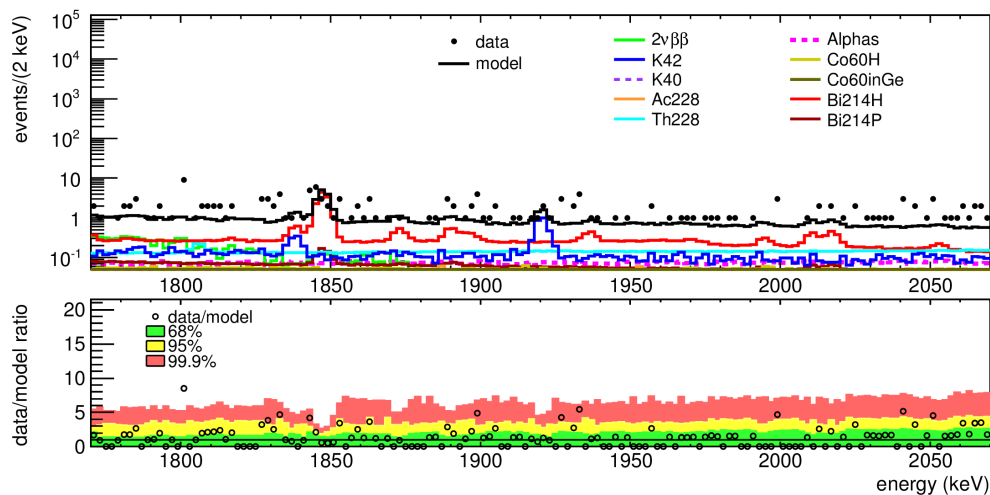
950 bins in total:
  3 bins outside red   (>99.9%) bands
 37 bins outside yellow (>95%)   bands
200 bins outside green (>68%)   bands

no hint for additional (strong) peaks

Note: bands are for integer valued intervals of the model with coverage at least as large as indicated → over-coverage especially for the green band & low counts

0νββ events: range 1 MeV electrons in Ge ~1 mm
   → one drift of electrons & holes, single site event (SSE)

background from γ's: range of MeV γ in Ge >10x larger
      → often sum of several electron/hole drifts,
         multi site events (MSE)

surface events: only electrons or holes drift

→ pulse shape discrimination (PSD) to select 0νββ events

weighting potential Φ

ionization

semi-coaxial

n+ contact

BEGe

Charge and current signal for BEGe detectors (data events)
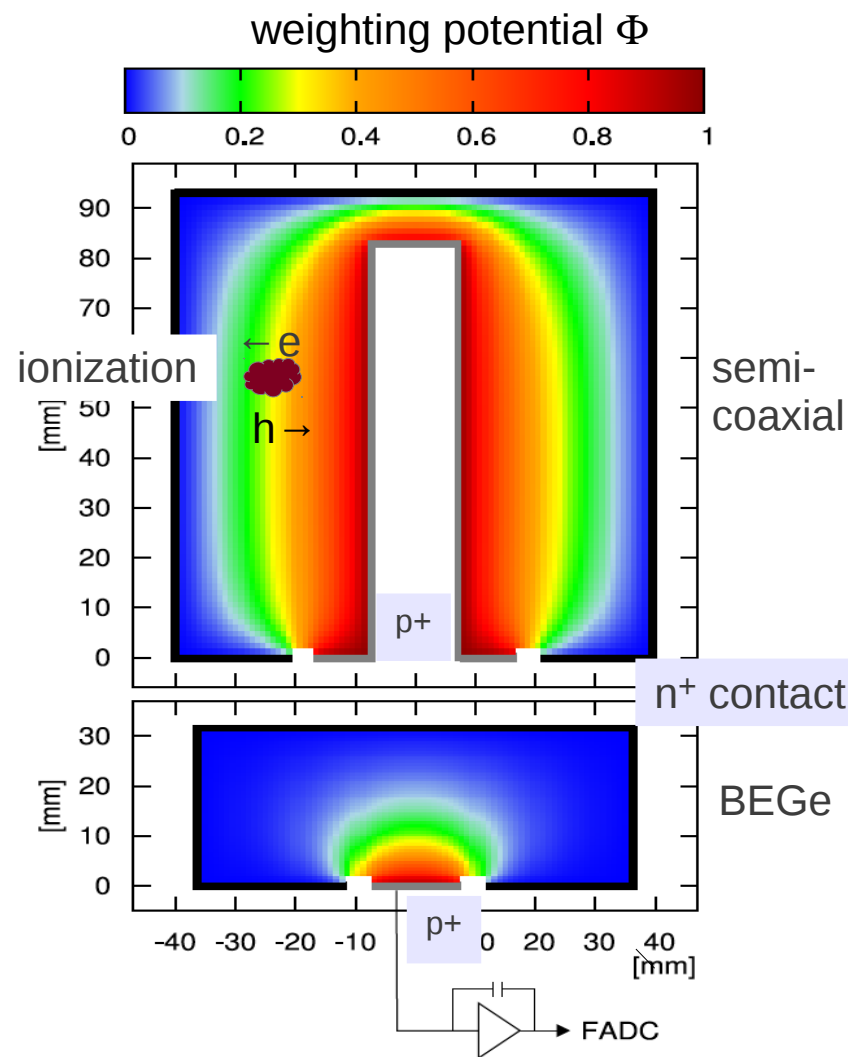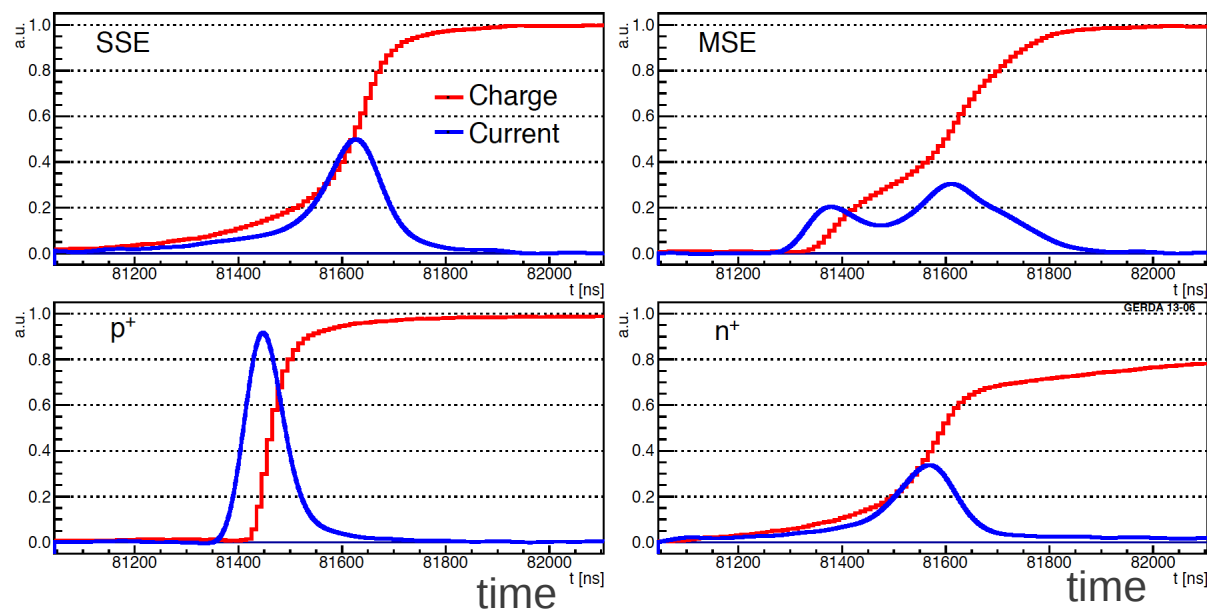
$$\text{current signal} = q \cdot v \cdot \nabla \Phi$$

q= charge, v = velocity
(Shockley-Ramo theorem)

PSD for BEGe

Develop the PSD method with calibration data and then apply it to physics data
double escape peak (DEP) events of 2615 keV γ in ^{228}Th spectrum are (mainly) SSE → proxy for $0\nu\beta\beta$

A/E = max. of current pulse "A" / energy "E" is robust & simple & well understood
accept events $0.965 < A/E < 1.07$ (normalization A/E for DEP events = 1)

A/E versus E for physics data
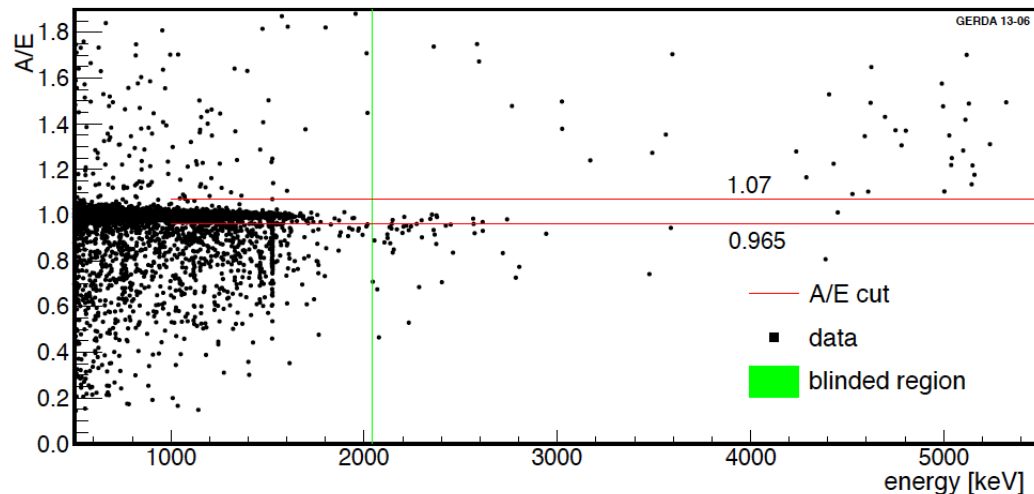
spectrum before (grey) & after (blue) cut
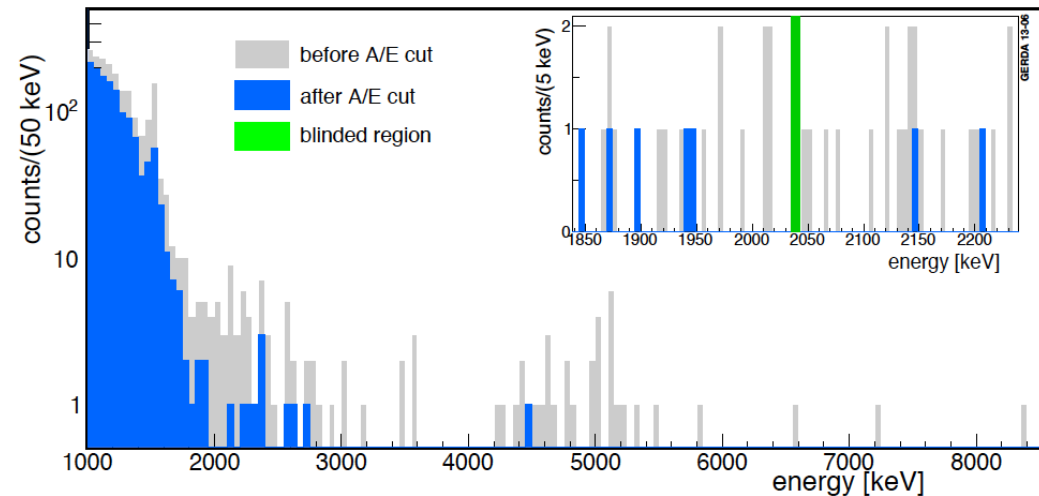
$0\nu\beta\beta$ efficiency = 92±2 % determined from DEP efficiency & simulation
$2\nu\beta\beta$ efficiency = 91±5 % in good agreement to DEP efficiency
reject >80% of background events

PSD for semi-coaxial: neural network

Input: time when charge signal reaches 1%, 3%, …, 99% of maximum

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- **1621 keV peak, background like**
- **DEP at 1592 keV, signal like**

intensity [a.u.]

time @ amplitude = 5% of max   time @ 91%

time

example: ANG3 ANN response, 1st period

DEP survival   90%

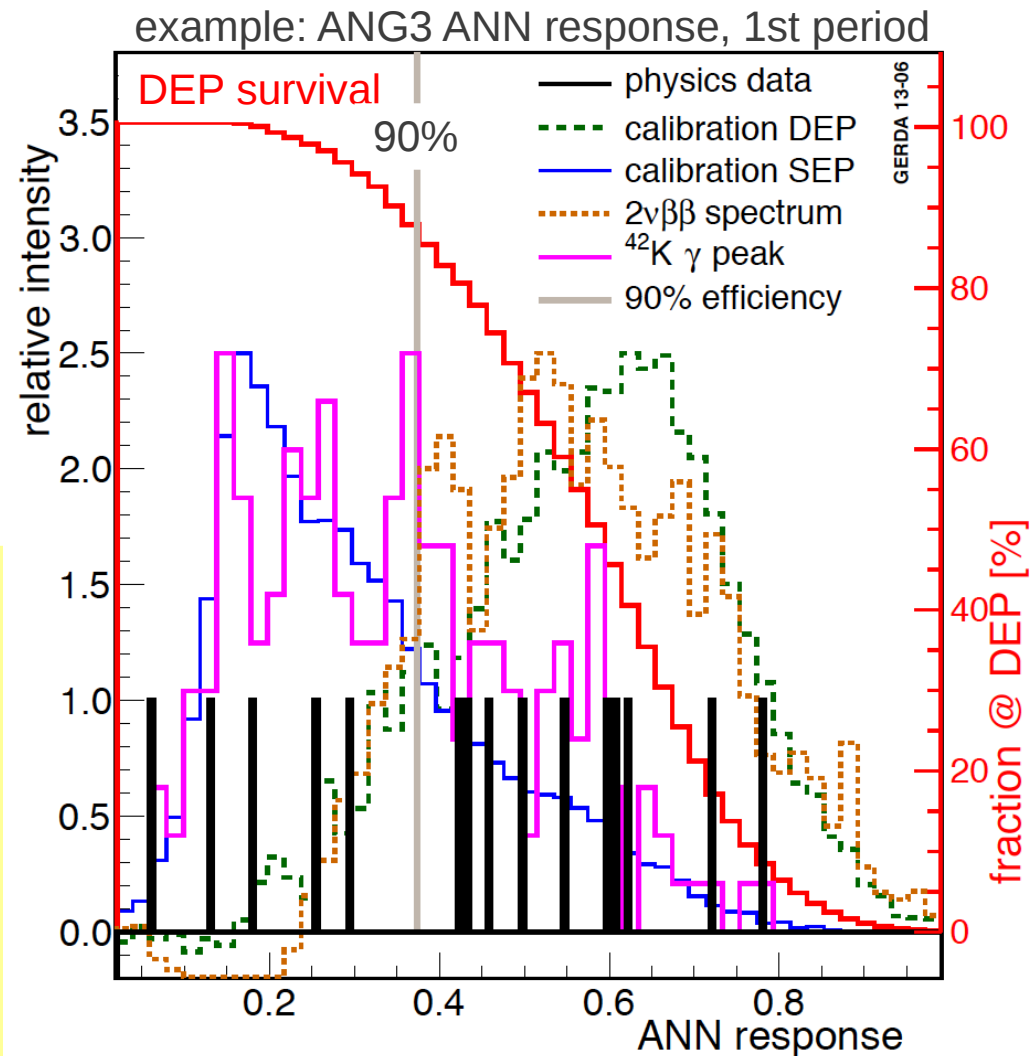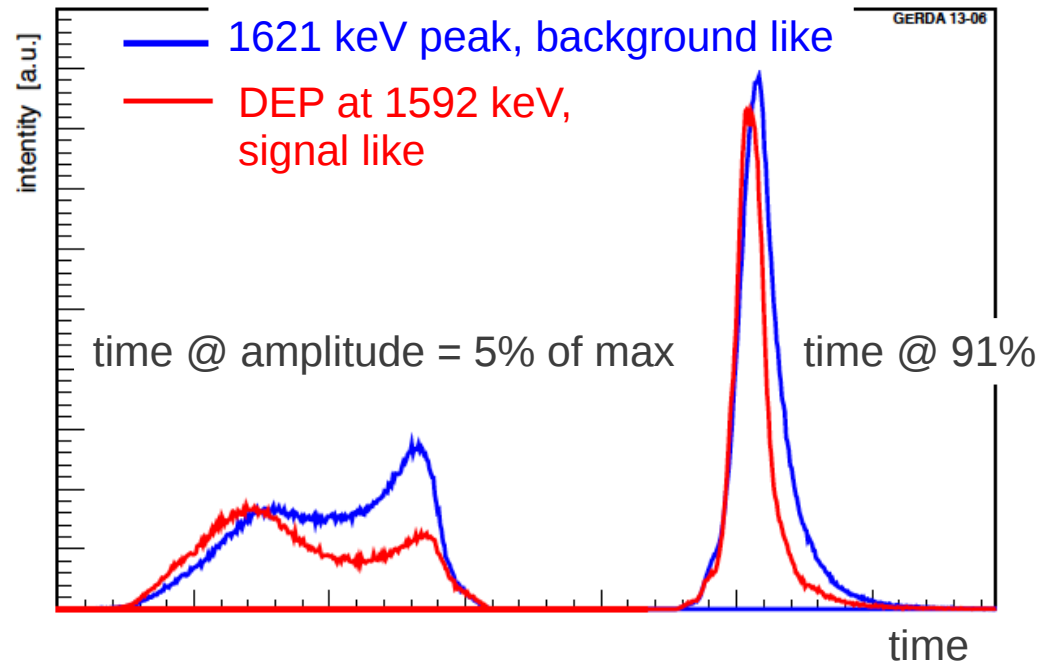- physics data
- calibration DEP
- calibration SEP
- $2\nu\beta\beta$ spectrum
- ^{42}K γ peak
- 90% efficiency

relative intensity

fraction @ DEP [%]

ANN response

GERDA 13-06

tested many methods implemented in TMVA, selected artificial neural network TMlpANN

select ANN cut position @ DEP survival = 90%

cross checks:
$2\nu\beta\beta$ eff. = 85±2 %,
2.6 MeV γ Compton edge eff. = 85-94%,
^{56}Co DEP (1576 keV) eff. = 83%-95%
^{56}Co DEP (2231 keV) eff. = 83%-93%

$$0\nu\beta\beta \text{ efficiency} = 0.90^{+0.05}_{-0.09}$$

PSD for semi-coaxial

calibration data

physics data
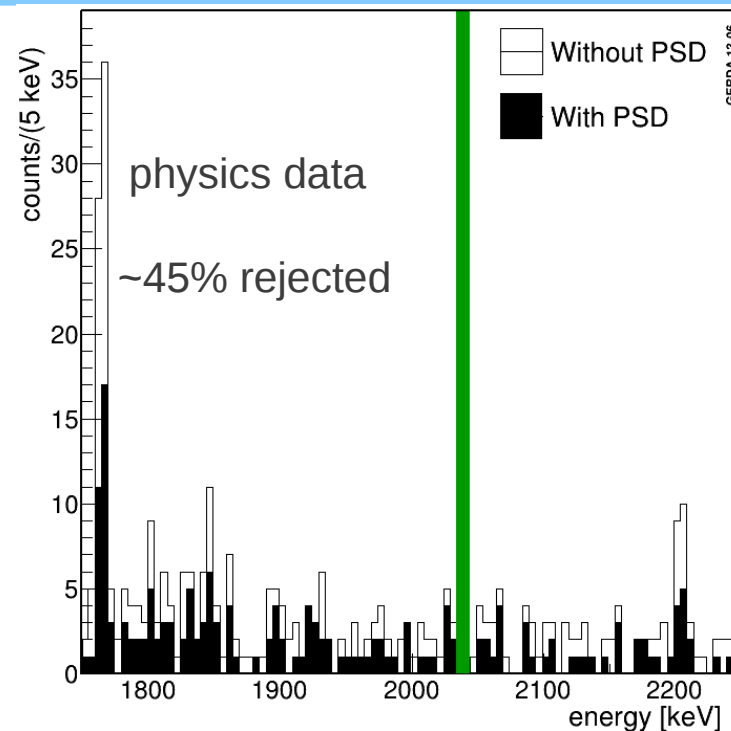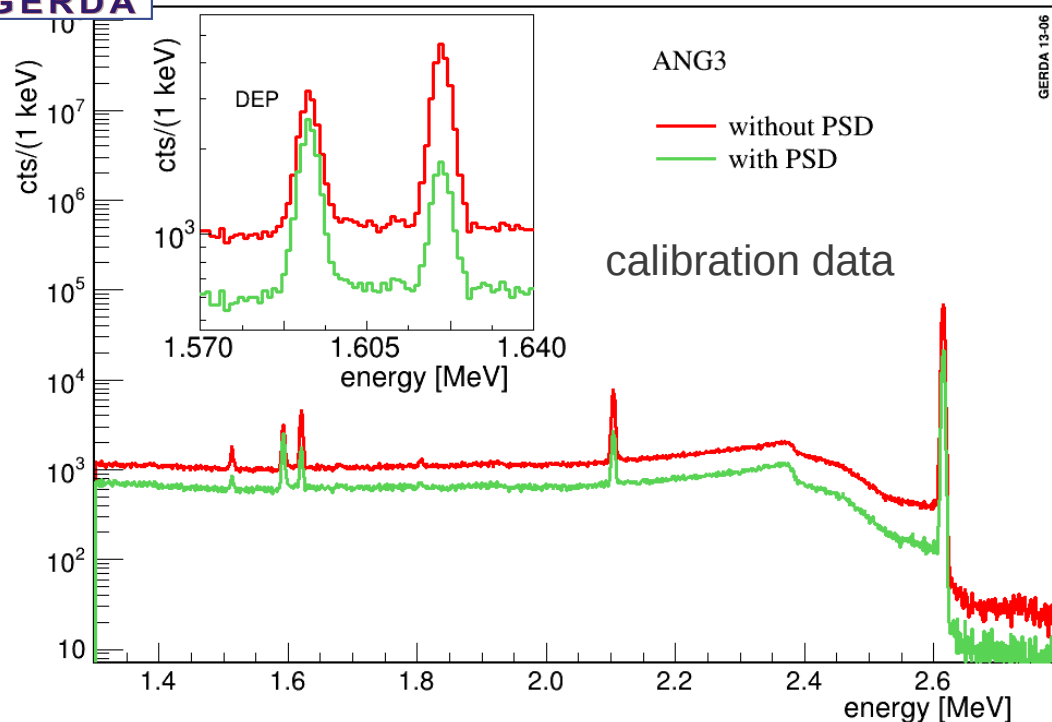
~45% rejected

overlap rejected physics events by 3 methods
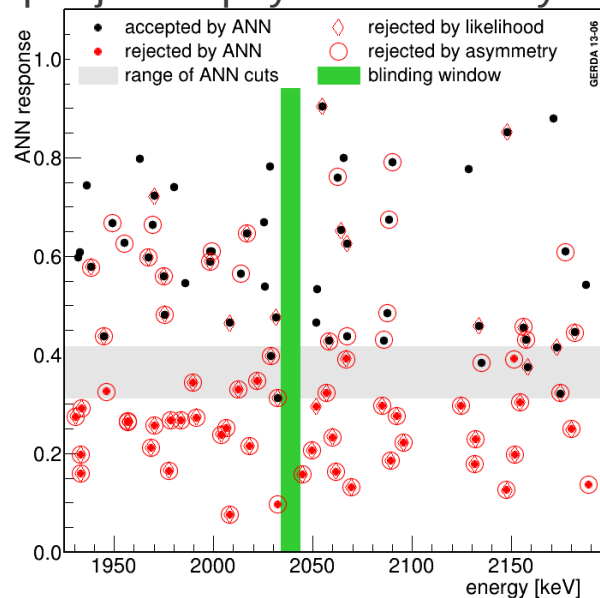
cross check ANN classification with 2 other methods:
1) projective likelihood trained with Compton edge evt
2) "current pulse asymmetry * A/E"

90% of ANN rejected events also rejected by both,
3% only rejected by ANN
→ classification of background like events meaningful

GERDA 13-07
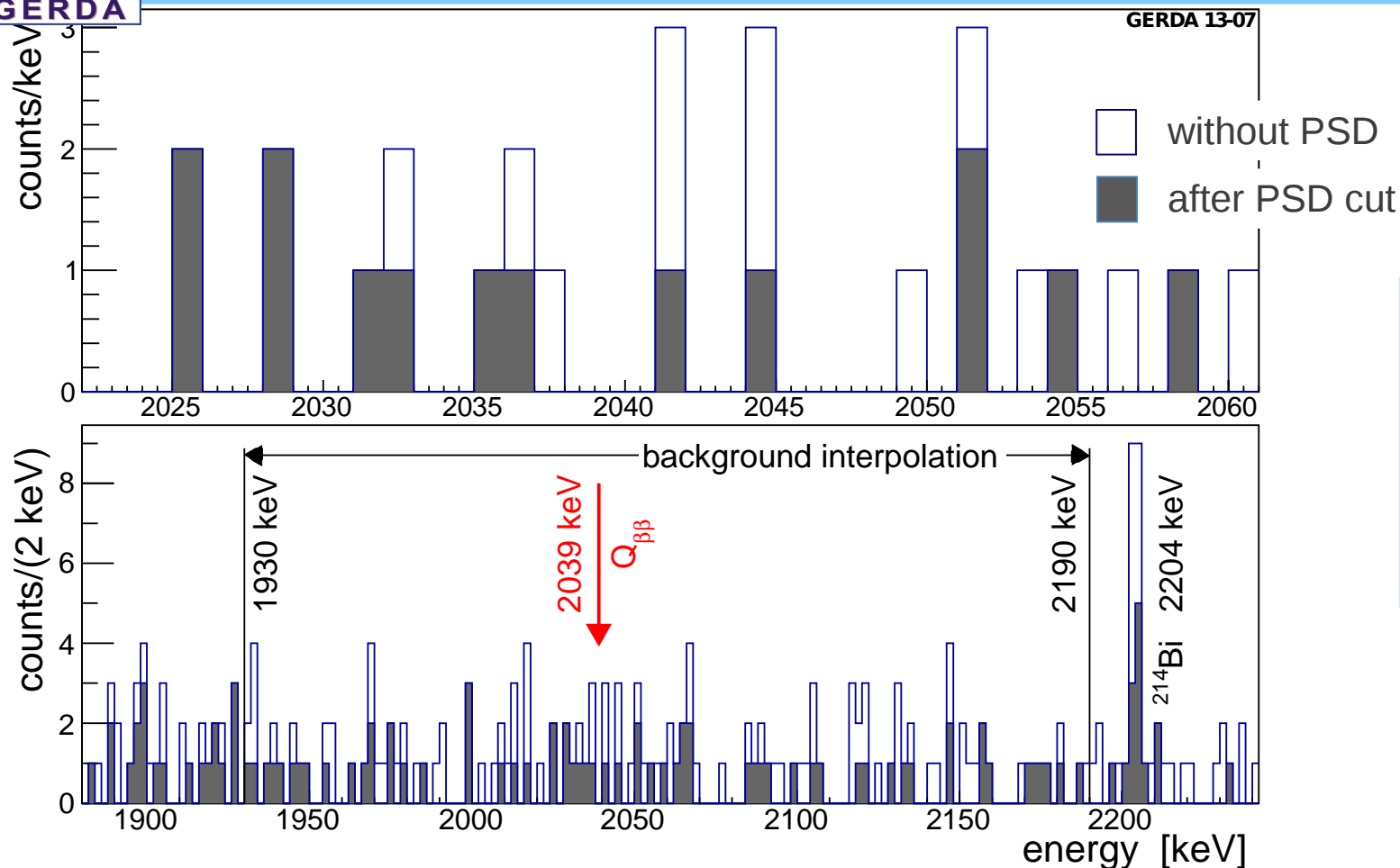
after calibration finished
& data selection frozen
& analysis method fixed
& PSD selection fixed

→ unblinding $Q_{\beta\beta} \pm 5$ keV
   @ meeting in Dubna

evt cnt in ±5 keV	golden	silver	BEGe	total
expt. w/o PSD	3.3	0.8	1.0	5.1
obs. w/o PSD	5	1	1	7
expt. w/ PSD	2.0	0.4	0.1	2.5
obs w/ PSD	2	1	0	3

No peak in spectrum at $Q_{\beta\beta}$,
event count consistent with bkg,
→ GERDA sets a limit

Half life limit for ^{76}Ge $0\nu\beta\beta$

$$T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} M \cdot t \cdot f_{76} \cdot f_{av} \cdot \epsilon_{fep} \cdot \epsilon_{psd}$$

exposure averaged efficiencies

data set	M*t	f_{76}	f_{av}	ϵ_{fep}	ϵ_{psd}
golden	17.9 kg yr	0.86	0.87	0.92	0.90
silver	1.3 kg yr	0.86	0.87	0.92	0.90
BEGe	2.4 kg yr	0.88	0.92	0.90	0.92

fit 3 data sets in 1930-2190 keV interval: constant (for bkg) + gauss (for signal),

4 parameters: 3x bkg level & $1/T^{0\nu}$
$1/T^{0\nu} > 0$ constrain

fix gaussian μ=(2039.06±0.2) keV, σ=(2.0±0.1)/(1.4±0.1) keV for coax/BEGe

systematic uncertainties on f, ε, μ, σ: Monte Carlo sampling & averaging

Frequentist: profile likelihood fit → best fit $N^{0\nu}=0$, $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.)   (sensitivity = 2.4 10^{25} yr)

Bayes: flat 1/T prior 0 - 10^{-24} yr → best fit $N^{0\nu}=0$, $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr (90% C.I.)   (sensitivity = 2.0 10^{25} yr)

adding HdM [1] & IGEX[2] spectra to profile likelihood fit → $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr (90% C.L.)   for ^{76}Ge

Assuming the claimed signal [3] GERDA should see 5.9±1.4 $0\nu\beta\beta$ events in ±2σ interval above bkg = 2.0±0.3,
→ probability p($N^{0\nu}=0$ | H_1=signal+bkg) = 1%, claim ruled out @ 99%
→ Bayes factor H_1(=signal+bkg) / H_0(=bkg only) = 0.024
combing with EXO-200 & Kamland-Zen using weakest exclusion (= smallest NME ratio ^{136}Xe/^{76}Ge ~ 0.4)
gives total Bayes factor H_1/H_0 = 0.0022 → claim of ^{76}Ge signal is strongly disfavored

[1] Euro Phys J A12 (2001) 147. [2] Phys Rev D65 (2002) 092007. [3] $T_{1/2}(^{76}$Ge)=1.19x10^{25} yr, Phys Lett B586 (2004) 198.

What value of Klapdor-Kleingrothaus to compare with?

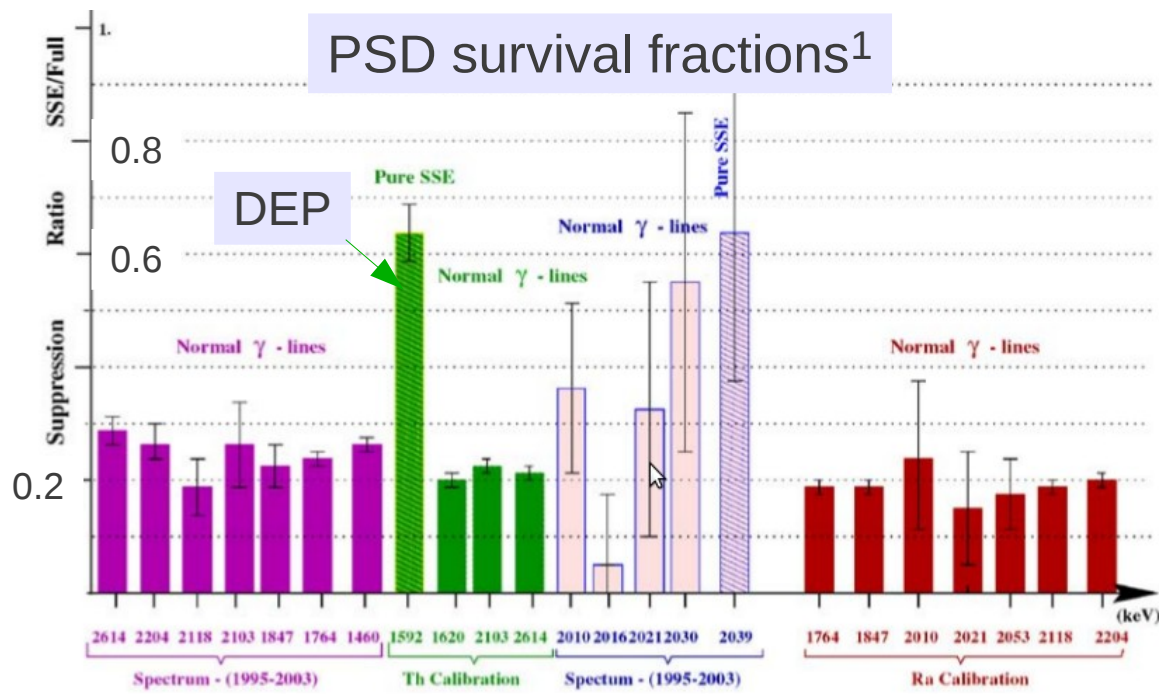a) 2004 publications: [1] NIM A522 371 & [2] Phys Lett B586 198

71.7 kg·yr

$Q_{\beta\beta}$
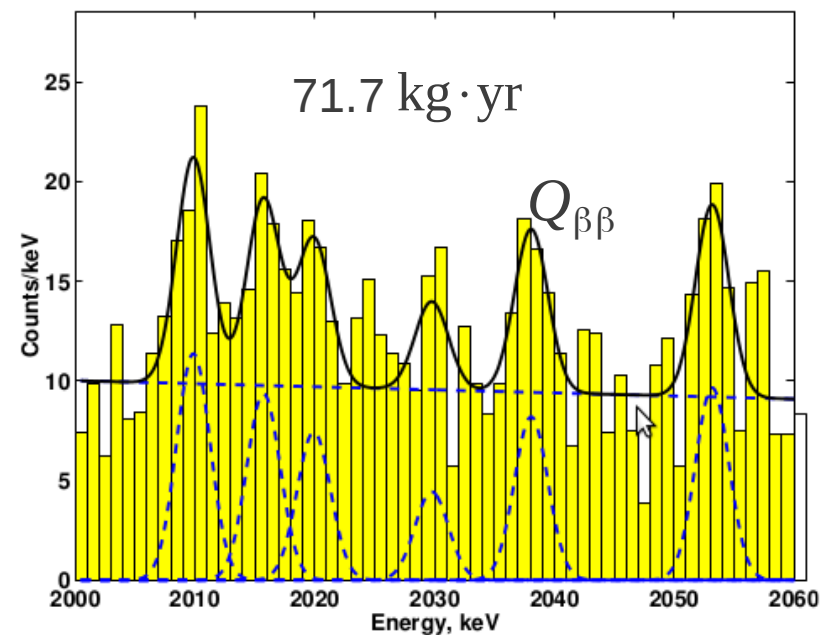
entire data set [1.2]: 71.7 kg·yr (active mass)
28.75 ± 6.86 signal events

$$T_{1/2}^{0\nu} = \left(1.19_{-0.23}^{+0.37}\right) \cdot 10^{25}\,\text{yr}$$ (our reference)

data for PSD analysis [1,2] 51.4 kg·yr
19.58 ± 5.41 signal events (total)
$$T_{1/2}^{0\nu} = \left(1.25_{-0.27}^{+0.49}\right) \cdot 10^{25}\,\text{yr}$$

PSD survival fractions[1]

DEP

with PSD: 12.36 ± 3.72 evt
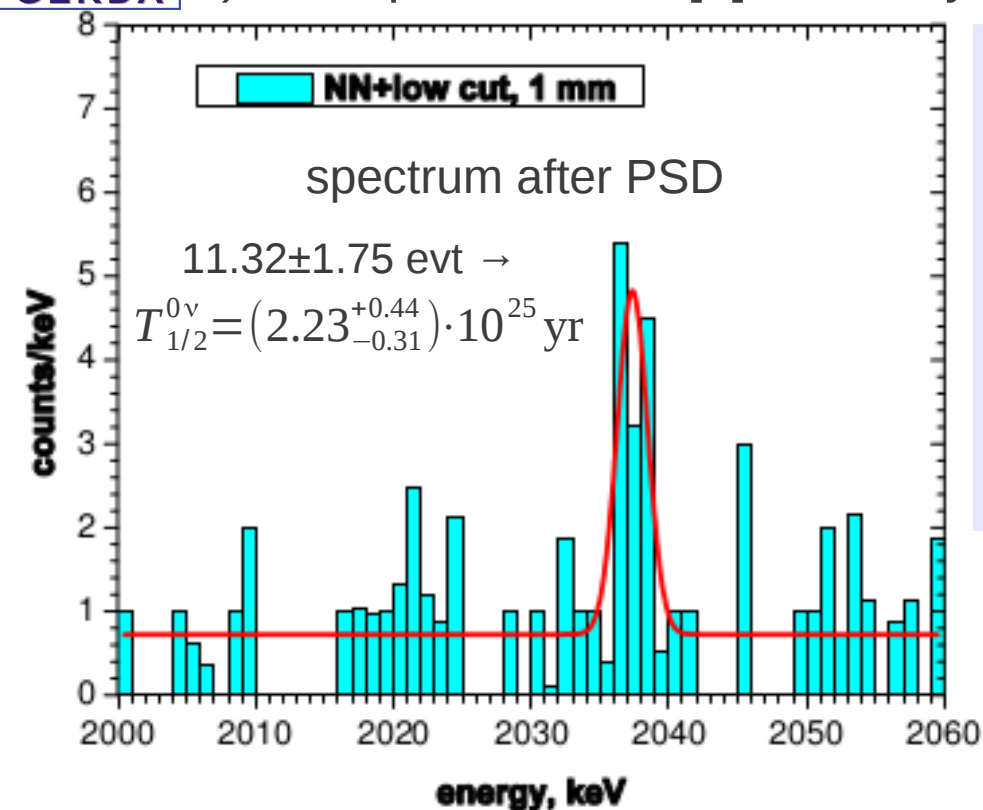Without efficiency correction
$$T_{1/2}^{0\nu} = 1.98 \cdot 10^{25}\,\text{yr}$$

DEP survival fraction [1] ~ 62%
$$T_{1/2}^{0\nu} = 1.23 \cdot 10^{25}\,\text{yr}$$ (my calculation)

No efficiency correction is applied in any publication!

using given eff., $T_{1/2}^{0\nu}$ after PSD agrees with 1.19 10^{25} yr

spectrum after PSD

11.32±1.75 evt →

$$T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25} \, \text{yr}$$

PSD based on 3 previous methods
(2 neural networks + pulse boardness)
& library of SSE pulses:
Event accepted IF pulse in library OR
found by neural network of Ref. 16 but
not by the other two neural networks

NO event overlap between the 2 sets!?

statement of publication:
- "multi site events are suppressed by 100%",
– 0νββ PSD efficiency = 1 used for $T^{0\nu}_{1/2}$

error on signal count not correct
since smaller than Poisson error

efficiency factor not considered
→ calculation of $T^{0\nu}_{1/2}$ not correct
→ GERDA does not use this result

Peak position shifted by -1.6 keV, why? "seem to be due to ballistic deficit" of SSE [3].
 a) effect should have opposite sign and b) should also apply to DEP (not discussed)
→ interpretation that peak @ 2039 keV is sum of 2 lines (DARK 2007 proc.) not supported by any argument
→ reduced count in line is due to efficiency of PSD

for discussion see also: Annalen d Phys 525 (2013) 269. J High Energy Phys 02 (2013) 093.

- GERDA has accumulated 21.6 kg yr of data,
  BI ~ 0.01 cts/(keV kg yr) after PSD

- GERDA has performed a blind analysis (first time in this field)

- Observe 3 events in $Q_{\beta\beta} \pm 5$ keV with expected bkg of 2.5±0.3
  $\rightarrow$ no signal

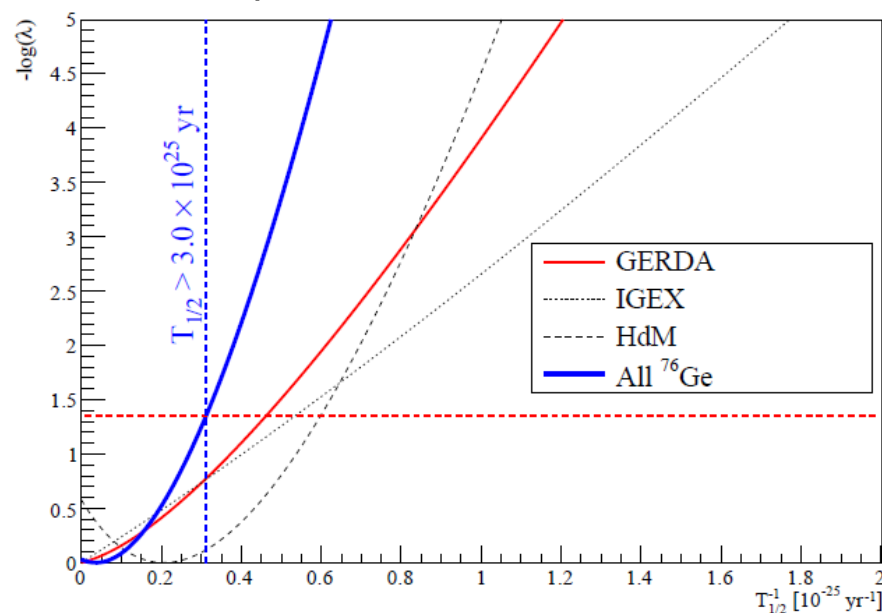- Profile likelihood fit $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) for ^{76}Ge

The claimed signal (without PSD) is ruled out by GERDA at 99% (without any model dependence)

$T^{0\nu}_{1/2}$ (central value & error) of the KK analysis with PSD is not correct

backup

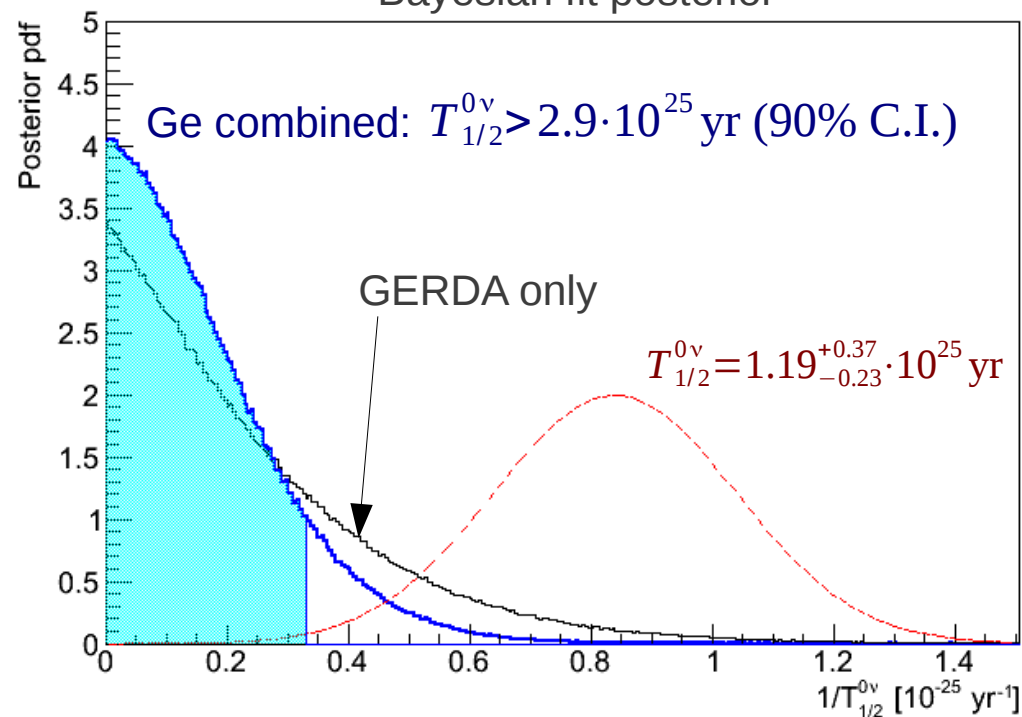Table 1: List of all events within $Q_{\beta\beta} \pm 5$ keV

data set	detector	energy [keV]	date	PSD passed	ANN	A/E	Cut Threshold
golden	ANG 5	2041.8	18-Nov-2011 22:52	no	0.344		0.366
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes	0.518		0.366
golden	RG 2	2041.3	16-Dec-2012 00:09	yes	0.682		0.364
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no		0.750	0.965÷1.070
golden	RG 1	2035.5	29-Jan-2013 03:35	yes	0.713		0.372
golden	ANG 3	2037.4	02-Mar-2013 08:08	no	0.205		0.345
golden	RG 1	2041.7	27-Apr-2013 22:21	no	0.369		0.372

profile likelihood fit

Bayesian fit posterior

Ge combined: $T^{0\nu}_{1/2} > 2.9 \cdot 10^{25}$ yr (90% C.I.)

GERDA only

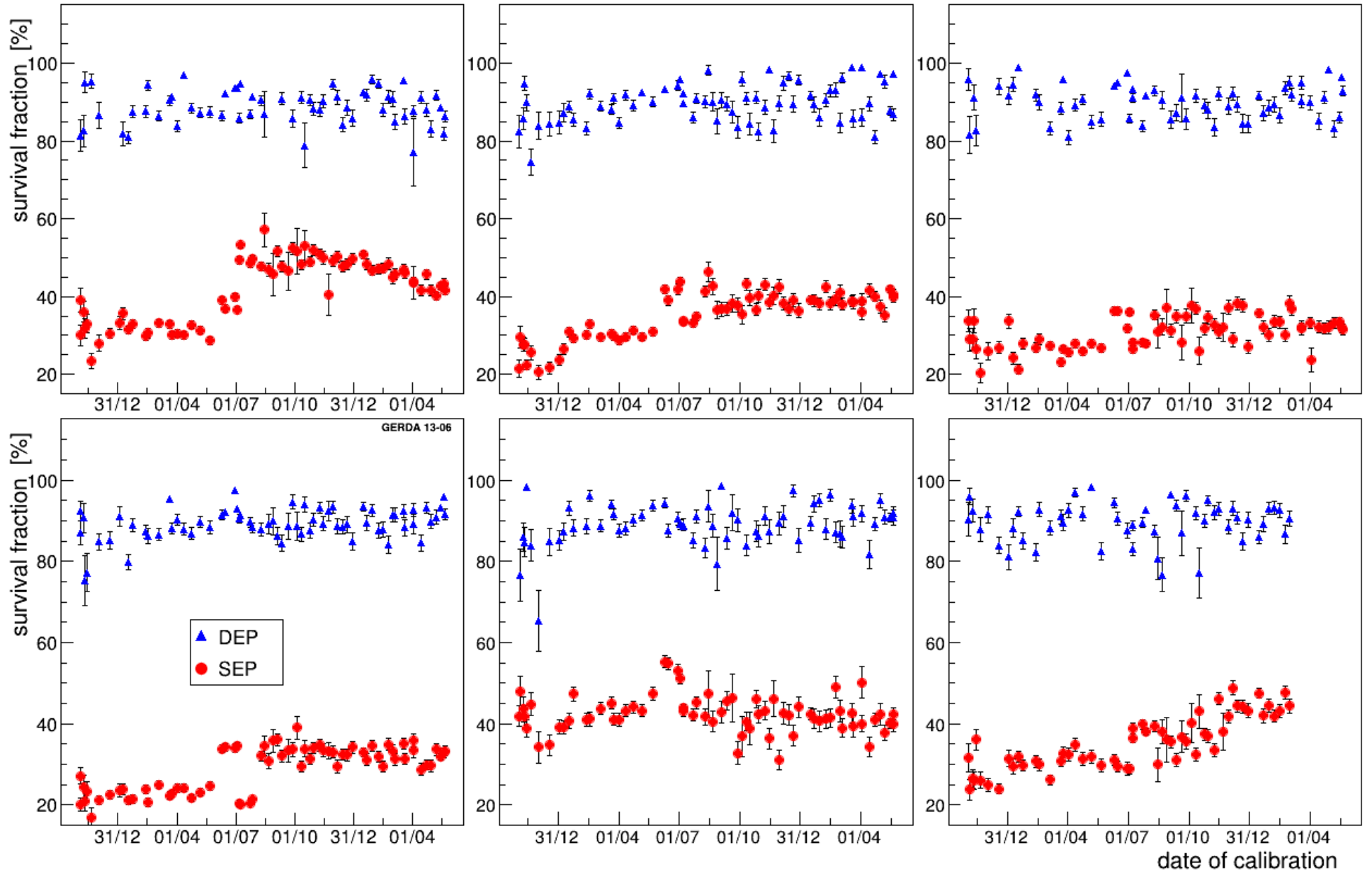$T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr

TAUP 2013 · GERDA result · 20

Time dependence of DEP and SEP survival fraction for different calibrations

GERDA 13-06

comparison of lower half life limits

GERDA result